ANALYSIS OF ACOUSTIC EMISSION FROM IMPACT AND FRACTURE OF CFRP LAMINATES

KANJI ONO, YOSHIHIRO MIZUTANI\textsuperscript{1} and MIKIO TAKEMOTO\textsuperscript{2}
Department of Materials Science and Engineering, UCLA, Los Angeles, CA 90095-1595, USA; \textsuperscript{1}Tokyo Institute of Technology, Ookayama, Meguro, Tokyo 152-8552, Japan; \textsuperscript{2}Faculty of Science and Engineering, Aoyama Gakuin University, Sagamihara, Kanagawa 229-8558, Japan

Abstract

The impact damage of CFRP plates under impact load was evaluated using recording of AE, load and strain history. The threshold or critical impact force to cause internal damage in cross-ply CFRP laminates was determined using dynamic surface strain and Lamb-wave AE along with the impact force history. Loading was conducted in SACMA-type impact tests at 0.8 and 1-m/s velocity. Four types of cross-ply CFRP plates ($[0^\circ/n/90^\circ/n]_s$, $n = 4-10$) are impacted with a spherical steel-tup. Lamb-wave AE signals were detected by small AE sensors on both surfaces. Polarity of AE signals detected by both sensors are used in studying the progression of fracture. Only impact-induced AE (or Impact-AE) is obtained when the impact tup contacts the specimen at a lower speed. When internal fracture occurs, both Impact-AE and fracture-induced AE (Fracture-AE) were detected. The nature of Fracture-AE is examined in this study in conjunction with ultrasonic C-scan and surface evaluation. AE monitoring on both surfaces enabled us to clearly separate the $S_0$ and $A_0$ modes of Lamb-wave AE signals. Most of strong AE signals correlated with matrix fracture source, while other damages had no associated distinctive events.

Keywords: Impact-AE, fracture-AE, CFRP laminates, impact damage threshold

Introduction

Carbon-fiber reinforced plastics (CFRPs) are useful in a wide range of applications due to their high specific strength and stiffness. However, they are prone to impact damage even under modest hits. SACMA-type impact test is often used for investigating impact fracture of CFRPs [1]. Only load history and tup velocity are taken during the test, after which samples are subjected to compression testing. We added AE monitoring and strain sensing to the SACMA tests and obtained the impact damage threshold for CFRP plates [2]. In so doing, in lieu of limited data, i.e., maximum impact load, impact duration and energy, we found details of the dynamic fracture processes in the form of Lamb-wave AE signals as well as displacement and surface strain history. Two types of AE signals were identified; Impact-AE and Fracture-AE. Only a limited number of previous studies have been reported on impact damages with little materials analysis [3-6], despite abundant CFRP studies of compression after impact are known.

In this study, waveforms of Lamb-wave AE signals due to internal damage in cross-ply CFRP laminates are examined, in conjunction with dynamic surface strain and the impact force history measured during SACMA-type impact tests. In particular, two-surface sensing [7-9] allowed us to evaluate mode types of detected signals. Additionally, failure modes were examined using microscopic studies to determine crack length and types and using ultrasonic C-scan to reveal the extent of delamination. Results are compared to the observations during quasi-static tests of the same CFRP.
Specimen and Experimental Setup

A large-size plate of ([0°₀/90°₀]ₙ), n = 4, 6, 8, 10) was prepared by laminating pre-pregs. Carbon fibers were pitch-based XN-50 from Nippon Graphite Fiber with the nominal modulus of 490 GPa. Rectangular specimens with 150 mm×100 mm were cut with the fiber directions (0°) on the top surface along the longitudinal (or X-) direction. Impact tests used Dynatup 8250 from Instron Corp., which satisfied SACMA SRM 2R-94 standard. Impact load was applied at the center of a specimen via a hemispherical steel tup of 16-mm diameter, weighing 3.61 kg [2]. The edges of the specimen were clamped all around by steel flanges. Four small AE sensors (Physical Acoustic Corp.: Type Pico) were mounted on both surfaces at 32-mm from the impact point in the X-direction. Polarity of AE signals detected by both sensors are compared for investigating the progression of fracture. A top AE sensor was used for determining the damage initiation. Outputs of two of the AE sensors were amplified 40 dB and filtered by a band-pass filter of 200 kHz to 1.2 MHz for eliminating large-amplitude low-frequency AE due to impact. The other two outputs were recorded directly at 10-1200 kHz bandwidth. As signal saturation occurred with amplification, all the analysis here used only direct-recording data. These signals were digitized by 2 PAC MISTRAS boards at the sampling interval of 500 ns over 10.2 ms, and stored in computers. The strain gage was attached on the top surface at the 32-mm from the impact point. Outputs of the strain gage and the load cell on the impact tup were digitized at the sampling interval of 1 μs over 60-ms period. The strain gage data was used for deciding impact damage threshold and timing. See [2] for other information. The tup displacement was dynamically recorded with a strain-gaged leaf-spring and used for velocity measurement.

Impact tests for four types of cross-ply CFRP plates ([0°₀/90°₀]ₙ) were conducted at two impact velocities (nominally 0.8 and 1 m/s) by controlling the height of the tup. Impact test for the 40-ply plate at 0.8 m/s was omitted, because no damage was observed at 1.0-m/s impact test. Details of quasi-static tests of similar CFRP plates were reported earlier and most fracture mechanisms are expected to operate under dynamic conditions as well.

Two-surface Sensing

In thin plates, Lamb waves are usually detected as AE signals. Figure 1 gives examples of 20-μs-long waveforms from in-plane (IP) and out-of-plane (OP) pencil-lead breaks. Two Pico sensors were placed on opposite faces of a 3.2-mm thick stainless steel plate, 50 mm from an edge. For comparison, the left figure is for an IP source with two sensors on the same side.

Two Pico sensors on the same side showed similar wave character for the first 7 peaks, but differences became prominent after ~8 μs. The first 3.6-μs portion is S₀ mode, but the arrival of A₀ mode cannot be discerned from these waveforms. IP source detected on two sides produced
nearly same waveforms for the first 6 peaks (~8 μs), indicating this part is S₀ mode. OP source (1 mm from the edge) showed the initial 4 peaks at the same phase, followed by 5 peaks at the opposite phases. The opposite phase waves are A₀ mode, while the initial part is S₀ mode. Such OP sources are often considered to generate primarily flexural modes, but this source was close to the edge and reflection contributed to the symmetric mode, albeit weaker.

It is clear that, with the two-side monitoring, we can distinguish symmetric (typically S₀) mode for the in-phase waves, while out-of-phase waves are asymmetric, flexural (typically A₀) mode. In CFRP plates used here, the calculated wave speed of S₀ mode varies widely; it is only about 15% faster than that of A₀ mode moving over the entire thickness at 500 kHz, and here the temporal separation of the two modes from a single source is not readily visible. However, faster propagating S₀ mode along the 0⁰-fibers exists with the measured velocity of 8-10 mm/μs without much dispersion. When S₀ mode or A₀ mode is found by itself, a distinct source is expected to have been active. See [7, 8] for more discussion on two-surface sensing.

![Fig. 2 Impact force-displacement-velocity vs. t](image1)

![Fig. 3 Impact force vs. displacement plot of 16-ply CFRP at 1 m/s nom. impact velocity.](image2)

### Impact History and Impact Damage

Measured impact force-displacement-velocity values are plotted against time in Fig. 2 for a 16-ply sample, hit at a nominal velocity of 1 m/s. The velocity at contact was 1.3 m/s, decreasing to zero at the peak load, from which point the tup reversed the direction as the load was reduced. The load vs. displacement plot is given in Fig. 3, which indicates the elastic loading and a sudden slope decrease (~45%) at 600 N, where damage initiated. A corresponding loading rate reduction is seen in Fig. 2. Most of bending displacement recovered upon unloading and the initial unload slope was unchanged from the load slope, implying minimal damage to the elastic stiffness of the plate. Directly recorded AE signals from Pico sensors are shown in Fig. 4. Early signals at 0.4 to 2.4 ms are Impact-AE (IAE) signals and have the flexural wave character. Fracture-AE (FAE) signals start at ~2.5 ms with 14 major events.

![Early signals at 0.4 to 2.4 ms are Impact-AE signals and have the flexural wave character. Fracture-AE (FAE) signals start at ~2.5 ms with 14 major events.](image3)

The first F-AE event coincides with the slope change of the load-time and load-displacement curves (cf. Figs. 2 and 3). This signal consists of a pair of S₀ and A₀ packets at 2.54 ms (Fig. 5a). The S₀ packet was 20-μs long, indicating the presence of fast through-fiber mode. This signal has a strong A₀ component, which is six times stronger than the S₀ packet preceding it (in p-to-p
Fig. 4 Direct recording of AE signals from bottom sensor. 16-ply sample hit nominally at 1 m/s. Most of top sensor signals are hidden.

Fig. 5 The first two major events in Fig. 4, each shown in 200-μs long segment for 2 sensors.
values). Most (11 of 14) of the recognizable AE events seen in Fig. 4 are of the type with both \( S_0 \) and \( A_0 \) components (Fig. 5a) and are marked with an asterisk. This signal type is almost identical to Type-D signal detected in the static tests of the same CFRP reported earlier [6, 7]. It was attributed to matrix fracture, found on the bottom surface under the impact point, splitting \( 0^\circ \)-fibers. This signal type (-D) was weaker, but similar in appearance to Type-A signal in the static testing, which was very strong (>2.5 \( V_{pp} \)) and was attributed to fiber fracture, which was observed on the top surface in real time using a video camera.

The second event starting at 2.77 ms (Fig. 5b) is mostly comprised of \( A_0 \) packets when top and bottom sensor signals have reasonable similarity (with inverting). We found three such signals, marked with an “o” in this test and referred to as Type-D’. Overall, these two events (Fig. 5a and b) resemble each other. The second type appears be of the same origin as the first except the weaker \( S_0 \) portion was disturbed by interference from the remnants of prior waves.

In this sample, a large matrix crack (53-mm long) was found on the bottom surface. The cross-sectional view of the plate (Fig. 6) shows this crack at the top. Delamination and fiber fracture are also observed in the middle layer. Delamination was extensive according to the observation by an air-coupled ultrasonic C-scan image (Fig. 7). The extent of damage spreads to as large as 42 x 15 mm double-tree shape area.

![Fig. 6 Cross-section of the 16-ply sample with arrow pointing to the matrix crack.](image)

![Fig. 7 Ultrasonic C-scan image of damaged area.](image)
It is significant to note that, in dynamic tests, Type-D (and -D') signals were prevalent, but not so strong (0.6 V peak maximum). This implies that the matrix crack proceeded stepwise under dynamic loading, although this is counter-intuitive. Stepwise development of the matrix crack is likely to be induced by the underlying fibers, which may have to be fractured to allow matrix crack propagation. In other test samples, delamination occurred between bottom-0° and 90° plies, and stepwise matrix crack growth was implied from AE findings. This point needs more study.

Another notable fact is the lack of AE signals that can be traced to the large delamination observed. All the major events are associated with the matrix crack and only the trailing parts of signals can explain delamination. It is feasible to recognize another signal type at 2.6 ms in Fig. 5a is, where a pair of S₀ and A₀ packets of similar amplitude are observed. This is characteristic of Type-C AE signals reported earlier for delamination between CFRP plies. This type is difficult to discern on waveform plots as many signals of various origins overlap as a rule. As the remaining waveform plots were surveyed, apparent S₀ and A₀ packets are also seen continually. However, distinct patterns fail to emerge. Despite extensive delamination observed, we found no distinctive AE type. It is likely that delamination developed continually without any sudden displacement jump. Under static loading, in contrast, nearly 20% of identified signals were Type-C, attributed to delamination. Also missing are signals (Type-B) previously assigned to transverse cracks (37% in the static test). These appear to constitute mostly A₀-mode signals that followed strong Type-D signals. These differences between static and dynamic tests are expected due to visco-elastic nature of polymeric fracture processes, which require further examination.

Three of six samples impacted at 1 m/s showed similar AE behavior described above. That is, over 60% of events were of Type-D and most of the remainder were Type-D'. The AE behavior of two other samples (24-ply and 32-ply plates, also impacted at 1 m/s) was slightly different as shown in Fig. 8. (Last one, 40-ply plate did not produce F-AE.) The first F-AE signal was detected at 2 ms and was of Type D (denoted with *) as before and the strongest signal was also of
Type-D (at 3.45 ms). In this sample, more $A_0$-only Type-D’ signals were observed as marked by an “o”. In the 32-ply sample, the ratio of D’ to D was the same; i.e., 2 : 1. In both cases, duration of F-AE observation was shorter (3 or 2 ms) than the 16-ply samples (~4 ms) due to higher stiffness of thicker plates. Thus, there are more overlaps of signals between strong events, probably converting Type-D into Type-D’.

Waveform of Type-D signal was previously simulated using the same CFRP and a line-focused laser pulse [6, 7]. Results are shown in Fig. 9, where the setup is at left, the waveform at center and its wavelet transform at right. The similarity of this waveform with that of Type-D is evident, including the period of the $S_0$ packet preceding the $A_0$ packet (20 $\mu$s) and the ratio of $A_0$ to $S_0$ amplitude (5.4 : 1). The frequency of the $S_0$ packet was higher in the simulation, reflecting the nature of the fast rise laser source. In the simulated waves, it is 500-600 kHz, whereas the $S_0$ frequency in Fig. 5 was 250-400 kHz. Observed $A_0$ frequency of ~140 kHz was comparable to the simulated $A_0$ packet frequency. It is noted here that the frequency of $A_0$ waves due to I-AE was much lower at 20-40 kHz.

Fig. 9 Laser simulation of matrix cracking on the bottom surface using focused laser beam parallel to the $0^\circ$ fibers. Pico sensor was 35 mm away (3 mm further than the present experiment).

Conclusions

This study reports on the utility of two-surface sensing in differentiating symmetric and asymmetric Lamb-wave modes. The method was applied to the monitoring of AE during the impact of CFRP plates of four different thicknesses. Different failure modes were seen under dynamic loading in comparison to quasi-static loading. A large matrix crack on the back surface and extensive delamination were the main features. AE signals attributable to matrix crack propagation were predominantly detected, while those due to delamination could not be discerned clearly. This was in marked contrast with the static case, where 4 separate failure mechanisms were correlated to 4 AE-signal types.

References

1) SRM 2R-94, SACMA Recommended Test Method for Compression After Impact, SACMA.


